

Electroweak Boson-Tagged Jet Event Asymmetries at the Large Hadron Collider

Ivan Vitev

Los Alamos National Laboratory, Theoretical Division, Mail Stop B283, Los Alamos, NM 87544, U.S.A.

Abstract

Tagged jet measurements provide a promising experimental channel to quantify the similarities and differences in the mechanisms of jet production in proton-proton and nucleus-nucleus collisions. We present the first calculation of the transverse momentum asymmetry of Z^0/γ^* -tagged jet events and the momentum imbalance of γ -tagged jet events in $\sqrt{s} = 2.76$ TeV reactions at the LHC. Our results combine the $\mathcal{O}(G_F\alpha_s^2)$, $\mathcal{O}(G_F\alpha_s^2)$ perturbative cross sections with the radiative and collisional processes that modify parton showers in the presence of dense QCD matter. We find that strong asymmetry momentum and imbalance, respectively, are generated in central Pb+Pb reactions that have little sensitivity to the fluctuations of the underlying soft hadronic background. We present theoretical model predictions for their shape and magnitude.

1. Introduction

Jets tagged by photons (γ) or electroweak bosons (W^\pm, Z^0) are particularly well suited to studying heavy-ion collisions [1] since the tagging particle escapes the region of strongly-interacting matter unscathed. For example, the CMS collaboration measurements in lead-lead (Pb+Pb) collisions show absence of significant modification of high transverse momentum Z^0 and photon production relative to the binary collision-scaled proton-proton (p+p) result within the current statistical and systematic uncertainties. Thus, in the collinear factorization approach Z^0 s and γ s can provide, on average, constraints on the energy of the away-side parton shower. Furthermore, jets tagged by photons or electroweak bosons are largely unaffected by the fluctuations of the soft hadronic background that may complicate the interpretation of di-jet modification in heavy-ion collisions. By selecting a suitable range for the transverse momentum of the tagging photon (p_{T_γ}), accessible at both RHIC and the LHC, the in-medium modification of parton showers in dense matter created at very different $\sqrt{s_{NN}}$ can be studied. In the jet suppression region, where the transverse momentum of the jet $p_{T_{\text{jet}}} \geq p_{T_{Z^0, \gamma}}$, the attenuation of inclusive jets [2, 3] and photon-tagged jets [4, 5] can be directly compared.

With this motivation, we present theoretical predictions for the cross section modification, growth in the transverse momentum asymmetry A_J , and imbalance z_J change of Z^0 -tagged and photon-tagged jet events in heavy ion collision and focus on LHC energies. These variables are defined as follows:

$$A_J = \frac{p_{T_{Z^0}} - p_{T_{\text{jet}}}}{p_{T_{Z^0}} + p_{T_{\text{jet}}}}, \quad z_{J\gamma} = \frac{p_{T_{\text{jet}}}}{p_{T_\gamma}}. \quad (1)$$

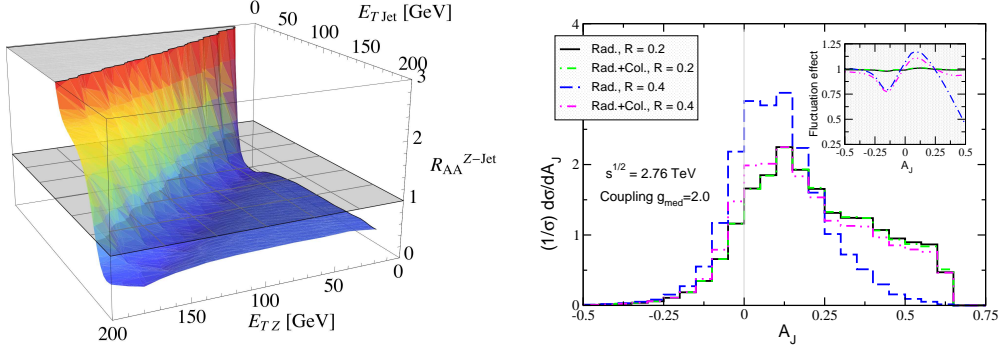


Figure 1: Left panel: tagged jet nuclear modification factor, $R_{AA}^{Z^0\text{-jet}}$, defined in Eq. (3), including both collisional and radiative energy loss effects. Our result is for $R = 0.4$ and coupling between the jet and the medium given by $g_{\text{med}} = 2$. Right panel: Z^0/γ^* -tagged jet event asymmetry for p+p collisions at $\sqrt{s} = 2.76$ TeV for two different $R = 0.2, 0.4$. Predictions for central Pb+Pb collisions with radiative medium-induced energy loss are also presented. Inset shows the effect of fluctuations in the background subtraction.

Our results combine the $O(\alpha_{\text{em}}\alpha_s^2)$, $O(G_F\alpha_s^2)$ perturbative cross sections with initial-state cold nuclear matter effects, see for example [6], and final-state parton shower modification and energy dissipation in the QGP.

2. Asymmetry of Z^0 -tagged jet events at the LHC

The calculation of the double differential cross sections for electroweak boson-tagged jet events is simpler than the corresponding calculation [2] for di-jet events [7, 8]. The medium-modified tagged cross section per binary scattering is calculated as follows:

$$\frac{1}{\langle N_{\text{bin}} \rangle} \frac{d\sigma^{AA}}{dp_{T,Z^0,\gamma} dp_{T,\text{jet}}} = \sum_{q,g} \int_0^1 d\epsilon \frac{P_{q,g}(\epsilon)}{1 - [1 - f(R)]\epsilon} R_{q,g} \frac{d\sigma^{CNM}(p_{T,Z^0,\gamma}, \frac{p_{T,\text{jet}}}{1 - [1 - f(R)]\epsilon})}{dp_{T,Z^0,\gamma} dp_{T,\text{jet}}}. \quad (2)$$

In Eq. (2) $P_{q,g}(\epsilon)$ is the probability distribution that a fraction ϵ of the hard-scattered quark or gluon energy is converted to a medium-induced parton shower [1] and $R_{q,g}$ is the fraction of the corresponding hard-scattered partons. Part of the dependence of the jet cross section on the jet reconstruction parameters, such as the radius R , is contained in $d\sigma^{CNM}/dp_{T,\gamma} dp_{T,\text{jet}}$. More importantly, the fraction of the parton shower energy that is simply redistributed inside the jet due to final-state interactions $f(R)$ also depends on R [$f(R)_{R \rightarrow 0} \rightarrow 0$, $f(R)_{R \gg 1} \rightarrow 1$] [2]. The physics meaning of Eq. (2) is that the observed Z^0 , γ -tagged jet cross section in nucleus-nucleus reactions is a probabilistic superposition of cross sections where the jet is of higher initial transverse momentum $p_{T,\text{jet}}/[1 - [1 - f(R)]\epsilon]$.

Complete information for the cold nuclear matter (CNM) and quark-gluon plasma (QGP) effects is contained in the generalized jet nuclear modification factor, $R_{AA}^{Z^0,\gamma\text{-jet}}$, given by

$$R_{AA}^{Z^0,\gamma\text{-jet}}(p_{T,Z^0,\gamma}, p_{T,\text{jet}}; R) = \frac{d\sigma^{AA}}{dp_{T,Z^0,\gamma} dp_{T,\text{jet}}} \bigg/ \langle N_{\text{bin}} \rangle \frac{d\sigma_{pp}}{dp_{T,Z^0,\gamma} dp_{T,\text{jet}}}. \quad (3)$$

Our simulations include medium-induced parton splitting [9], here applied in the soft gluon approximation [10], and dissipation of the medium-induced parton shower energy in the QGP

due to collisional processes [11]. The nuclear modification factor provides a compact way to quantify the effects of the nuclear medium. Our predictions [12] for $R_{AA}^{Z\text{-jet}}$ ($R = 0.4$) are presented in the left panel of Fig. 1. Since part of the parton shower energy is redistributed outside of the jet cone radius, the jets are pushed to lower values of $p_{T\text{Jet}}$. This redistribution results in an enhancement in $R_{AA}^{Z\text{-jet}}$ in the region of $p_{T\text{Jet}} < p_{TZ}$ and suppression in $R_{AA}^{Z\text{-jet}}$ in the region of $p_{T\text{Jet}} > p_{TZ}$, which is characteristic of in-medium tagged-jet dynamics [1].

Tagged jet asymmetry and imbalance are obtained by changing variables appropriately and integrating the remaining variable in the specified kinematic domain. For example,

$$\frac{d\sigma}{dA_J} = \int_{p_{T\text{Jet min}}^{p_{T\text{Jet max}}}} dp_{T\text{jet}} \frac{2p_{T\text{jet}}}{(1 - A_J)^2} \frac{d\sigma}{dp_{T_{Z^0}} dp_{T\text{jet}}}. \quad (4)$$

In the example that follows $p_{TZ} \in (80, 100)$ GeV and $p_{T\text{Jet}} > 20$ GeV. In the right panel of Fig. 1 we present the Z^0/γ^* -tagged jet event asymmetry for central Pb+Pb collisions with radiative (solid and dashed curves) and radiative+collisional (dot-dashed and dot-dot dashed curves) medium-induced energy losses. The collisional energy loss has a more pronounced effect in the curve with the larger radius. This occurs because collisional energy loss from a parton shower comes primarily from the radiated gluons, as demonstrated in [11]. With the smaller radius most of the gluons are already outside of the jet cone making the extra energy loss redundant. We point out that background fluctuations again have minimal effect when the collisional energy loss is included, as can be checked from the insert in Fig. 1. The result is a considerable shift in $\langle A_J \rangle$ and broadening of the asymmetry distribution.

3. Momentum imbalance of γ -tagged jet events at the LHC

The cross section for isolated photon-tagged jet events is also calculated as described in Eq. (2). The many-body QCD dynamics that modifies isolated photon + jet production in relativistic heavy-ion collisions is manifested in the deviation from the baseline p+p results, scaled by the number of binary nucleon-nucleon interactions, and is shown in the left panel of Fig. 2. Our results [5] are qualitatively similar to the modification of Z^0/γ^* tagged jets [12]. However, direct comparison between RHIC and LHC is possible for the first time in a more exclusive channel.

We can express the γ -tagged jet event momentum imbalance distribution as follows:

$$\frac{d\sigma}{dz_J} = \int_{p_{T\text{jet}}^{\min}}^{p_{T\text{jet}}^{\max}} dp_{T\text{jet}} \frac{p_{T\text{jet}}}{z_J^2} \frac{d\sigma[z_J, p_{T_\gamma}(z_J, p_{T\text{jet}})]}{dp_{T_\gamma} dp_{T\text{jet}}}. \quad (5)$$

In our p+p and Pb+Pb calculations at the LHC we use the CMS experimental cuts [4] $p_{T\text{jet}} > 30$ GeV, $p_{T_\gamma} > 60$ GeV, $|y^\gamma| < 1.44$, $|y^{\text{jet}}| < 1.6$, $|\phi^{\text{jet}} - \phi^\gamma| > \frac{7}{8}\pi$. We implement a k_T algorithm with a radius parameter $R = 0.3$ for the jet and isolation criterion that requires the total energy within a cone of radius $R_{\text{iso}} = 0.4$ surrounding the photon direction to be less than 5 GeV. The normalized momentum imbalance distribution $(1/\sigma)d\sigma/dz_J$ is given in the right panel of Fig. 2. The solid black line shows the p+p calculation and the circles represent the CMS result with large error bars [4]. The dotted cyan line includes cold nuclear matter effects in central Pb+Pb reactions. These CNM effects do not affect the z_J distribution appreciably. The physics responsible for the difference between p+p and A+A reactions is then contained in the final-state QGP-induced parton splitting and the dissipation of the parton shower energy in the medium.

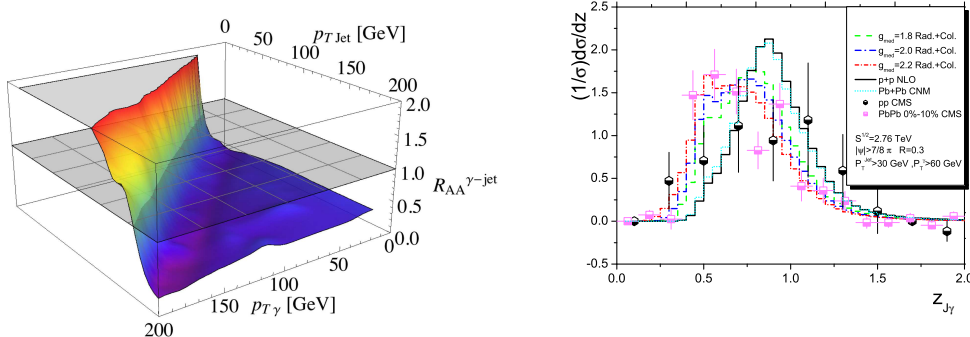


Figure 2: Left panel: the nuclear modification factor $R_{AA}^{\gamma\text{-jet}}$ for the isolated photon-tagged jets in the most central Pb+Pb reactions ($R=0.3$) at $\sqrt{s_{NN}} = 2.76$ TeV. Right panel: the isolated photon-tagged jet asymmetry distribution for different coupling strengths between the jet and the medium. Black and magenta points are CMS experimental data in p+p and Pb+Pb collision, respectively.

The parameter that controls the strength of the coupling between the jet constituents and the strongly interacting matter is g_{med} . We investigate a range of values $g_{\text{med}} = 1.8$ (green dashed), 2.0 (blue dot – dashed), 2.2 (red short dot – dashed) that has worked well in describing the di-jet asymmetry distribution and in predicting the inclusive jet suppression at the LHC [2]. The same range of coupling strengths has been used to predict the asymmetry distribution of Z^0 +jet events in heavy-ion collisions [12].

4. Summary

We presented selected results from the first studies [5, 12] of the nuclear modification of Z^0 , γ -tagged jet cross sections and the corresponding changes in their transverse momentum asymmetry and momentum imbalance distributions. We found that a pQCD approach [2] that describes well the inclusive jet suppression [3] and enhancement of the di-jet asymmetry [7, 8] in heavy ion collisions at the LHC can predict the shape modifications (A_J , z_J) and cross section attenuation of the electroweak boson-tagged jet events recently measured by the ATLAS [13] and CMS [4] collaborations in $\sqrt{s} = 2.76$ TeV Pb+Pb collisions.

References

References

- [1] R. B. Neufeld, I. Vitev and B. -W. Zhang, Phys. Rev. C **83**, 034902 (2011).
- [2] Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B **713**, 224 (2012); B.-W. Zhang, these proceedings.
- [3] G. Aad *et al.* [ATLAS Collaboration], arXiv:1208.1967 [hep-ex].
- [4] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1205.0206 [nucl-ex].
- [5] W. Dai, I. Vitev and B. -W. Zhang, arXiv:1207.5177 [hep-ph].
- [6] R. Sharma, I. Vitev, arXiv:1203.0329 [hep-ph]; R. Sharma, these proceedings.
- [7] G. Aad *et al.* [Atlas Collaboration], Phys. Rev. Lett. **105**, 252303 (2010).
- [8] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. C **84**, 024906 (2011).
- [9] G. Ovanessian and I. Vitev, Phys. Lett. B **706**, 371 (2012); G. Ovanessian, these proceedings
- [10] I. Vitev, Phys. Rev. C **75**, 064906 (2007).

- [11] R. B. Neufeld and I. Vitev, Phys. Rev. C **86**, 024905 (2012).
- [12] R. B. Neufeld and I. Vitev, Phys. Rev. Lett. **108**, 242001 (2012).
- [13] J. Casalderrey-Solana, S. Milov, these proceedings; Z. Citron, these proceedings.